

# SPECIFICATION

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## [METHOD AND SYSTEM FOR INFERRING TORQUE OUTPUT OF A VARIABLE COMPRESSION RATIO ENGINE]

### Background of Invention

[0001] 1. Field of the Invention

[0002] The present invention relates generally to variable compression ratio internal combustion engines. More particularly, the invention relates to a method and system for determining the torque output of a variable compression ratio internal combustion engine.

[0003] 2. Background Art

[0004] The "compression ratio" of an internal combustion engine is defined as the ratio of the cylinder volume when the piston is at bottom-dead-center (BDC) to the cylinder volume when the piston is at top-dead-center (TDC). Generally, the higher the compression ratio, the higher the thermal efficiency and fuel economy of the internal combustion engine. So-called "variable compression ratio" internal combustion engines have been developed, for example, having higher compression ratios during low load conditions and lower compression ratios during high load conditions. Various techniques have been disclosed for varying compression ratio, including for example, using "sub-chambers and "sub-pistons" to vary the volume of a cylinder, see for example patents US 4,246,873 and US 4,286,552; varying the actual dimensions of all or a portion of a piston attached to a fixed length connecting rod, see US 5,865,092; varying the actual length of the connecting rod itself, see US 5,724,863 and 5,146,879; and using eccentric rings or bushings either at the lower "large" end of a

connecting rod or the upper "small" end of the connecting rod for varying the length of the connecting rod or height of the reciprocating piston., see US Patent Nos. 5,562,068, US 5,960,750, US 5,417,185 and Japanese Publication JP-03092552.

[0005] As with conventional internal combustion engines, it is vitally important for a number of reasons to be able to accurately estimate the output torque of a variable compression ratio internal combustion engine. Torque estimates are used, for example, to schedule hydraulic line pressures in a step ratio transmission, prevent transmission braking in certain gears by limiting peak torque, and to coordinate operation of a vehicle's anti-lock braking system so as to minimize wheel slip. In vehicles having multiple torque sources, for example hybrid electric vehicles, torque estimates are required in order to properly coordinate and arbitrate the various torque sources onboard the vehicle.

[0006] The inventor herein has recognized the need to accurately determine the output torque as a function of a selected engine compression ratio in order to ensure optimal control and performance of the engine and corresponding motor vehicle.

## Summary of Invention

[0007] A method is provided for operating a variable compression ratio internal combustion engine. The method includes the steps of determining a compression ratio operating state of the variable compression ratio internal combustion engine, and inferring a torque output for the engine based at least in part on the compression ratio operating state of the engine. For example, in accordance with the present invention, brake engine torque can be inferred by determining an engine speed, air flow and current compression ratio operating state of the engine, and then selecting both a baseline indicated torque value and a baseline engine friction loss value based on the speed, air flow and compression ratio operating state of the engine. The baseline indicated torque and engine friction loss values are modified according to operating conditions and parameters of the engine, and then used to determine the brake engine torque.

[0008] Advantageously, the methods described herein allow for improved estimates of engine output torque that can be used to optimize scheduling of compression ratio

operating states in a variable compression ratio internal combustion engine. The methods disclosed herein are useful for optimizing the fuel economy benefits of the engine, while at the same time improving control and performance of a corresponding motor vehicle and related components and subsystems.

[0009] In accordance with a related aspect of the present invention, a corresponding system is provided for operating a variable compression ratio internal combustion engine. The system includes a compression ratio setting apparatus for configuring the engine in selected ones of the compression ratio operating states, and a controller in communication with the sensors and the compression ratio apparatus, the controller comprising computer program means for inferring a torque output for the engine based at least in part on the compression ratio operating state of the engine. The system in accordance with a preferred embodiment further includes a sensor coupled to the engine for generating a signal representative of engine speed, a sensor coupled to the engine for generating a signal representative of air flow into the engine; and computer program code and look-up tables for determining at least one predefined indicated torque value based on the engine speed, the air flow and the compression ratio operating state of the engine; and computer program code and look-up tables for determining at least one predefined engine friction loss value based on the engine speed, the air flow and the compression ratio operating state of the engine. The system further includes computer program code for estimating a brake torque of the engine using the indicated torque and baseline engine friction loss values.

[0010] Further advantages, objects and features of the invention will become apparent from the following detailed description of the invention taken in conjunction with the accompanying figures showing illustrative embodiments of the invention.

## Brief Description of Drawings

[0011] For a complete understanding of the present invention and the advantages thereof, reference is now made to the following description taken in conjunction with the accompanying drawings in which like reference numerals indicate like features wherein:

[0012] FIGURE 1 is a diagram of an exemplary variable compression ratio internal

combustion engine in accordance with the present invention;

[0013] FIGURE 2 is a block diagram showing the engine and controller of FIGURE 1 coupled to a driveline of a motor vehicle;

[0014] FIGURE 3 is a flow diagram of a preferred method for operating a discretely variable compression ratio internal combustion engine in accordance with the present invention; and

[0015] FIGURE 4 is a flow diagram of a preferred method for operating a continuously variable compression ratio internal combustion engine in accordance with the present invention.

## Detailed Description

[0016] FIGURE 1 shows an exemplary variable compression ratio internal combustion engine in accordance with the present invention. As will be appreciated by those of ordinary skill in the art, the present invention is independent of the particular underlying engine configuration and component designs, and as such can be used with a variety of different internal combustion engines having more than one compression ratio operating modes. The engine for example can be constructed and operated as a discrete compression ratio engine operating for example at a high compression or at low compression, or as a continuously variable compression ratio engine capable of operating at a any number of discrete or selected compression ratios. Similarly, the present invention is not limited to any particular type of apparatus or method required for setting or varying the compression ratio of the internal combustion engine.

[0017] Referring again to FIGURE 1, the engine 110 includes a plurality of cylinders (only one shown), each having a combustion chamber 111, a reciprocating piston 112, and intake and exhaust valves 120 and 118 for communicating the combustion chamber 111 with intake and exhaust manifolds 124 and 122. The piston 112 is coupled to a connecting rod 114, which itself is coupled to a crankpin 117 of a crankshaft 116. Fuel is provided to the combustion chamber 111 via a fuel injector 115 and is delivered in proportion to a fuel pulse width (FPW) determined by an electronic engine or vehicle controller 60 (or equivalent microprocessor-based controller) and electronic

driver circuit 129. Air charge into the intake manifold 124 is nominally provided via an electronically controlled throttle plate 136 disposed within throttle body 126. Ignition spark is provided to the combustion chamber 111 via spark plug 113 and ignition system 119 in accordance with a spark advance (or retard) signal (SA) from the electronic controller 60.

[0018] As shown in FIGURE 1, the controller 60 nominally includes a microprocessor or central processing unit (CPU) 66 in communication with computer readable storage devices 68, 70 and 72 via memory management unit (MMU) 64. The MMU 64 communicates data (including executable code instructions) to and from the CPU 66 and among the computer readable storage devices, which for example may include read-only memory (ROM) 68, random-access memory (RAM) 70, keep-alive memory (KAM) 72 and other memory devices required for volatile or non-volatile data storage. The computer readable storage devices may be implemented using any known memory devices such as programmable read-only memory (PROM's), electrically programmable read-only memory (EPROM's), electrically erasable PROM (EEPROM's), flash memory, or any other electrical, magnetic, optical or combination memory devices capable of storing data, including executable code, used by the CPU 66 for controlling the internal combustion engine and/or motor vehicle containing the internal combustion engine. Input/output (I/O) interface 62 is provided for communicating with various sensors, actuators and control circuits, including but not limited to the devices shown in FIGURE 1. These devices include an engine speed sensor 150, electronic fuel control driver 129, ignition system 119, manifold absolute pressure sensor (MAP) 128, mass air flow sensor (MAF, "airmeter") 134, throttle position sensor 132, electronic throttle control motor 130, inlet air temperature sensor 138, engine knock sensor 140, and engine coolant temperature 142.

[0019] The engine 110 of FIGURE 1 also includes and a variable compression ratio ("compression ratio setting") apparatus 170. In a non-limiting embodiment, the variable compression ratio apparatus 170 is operated to vary the effective length of the connecting rod 114, and thus the clearance volume and compression ratio of the engine. Such an apparatus is described, for example, in U.S. Application Serial No. 09/682,263, entitled "Connecting Rod for a Variable Compression Engine," which is owned by the assignee of the present invention and is hereby incorporated by

reference in its entirety. The actual construction and configuration of the variable compression apparatus shown in FIGURE 1 is not at all intended to limit the scope of claim protection for the inventions described herein.

[0020] In a non-limiting aspect of the present invention, the variable compression ratio apparatus of FIGURE 1 is described below as operating in a "high" compression ratio mode (compression ratio of 13:1 and above) or a "low" compression ratio mode (compression ratio of 11:1 and below).

[0021] FIGURE 2 shows a high-level block diagram of the engine 110 and controller 60 of FIGURE 1 coupled to a driveline 210 of a motor vehicle. The controller 60 is shown as a powertrain control module for controlling both engine and driveline operations for the motor vehicle. The driveline 210, by way of example and not limitation, includes a torque converter 212, a vehicle transmission 214, and axle 216. The driveline however may include other conventional vehicle driveline components such as the driveshaft, suspension, brakes, etc.

[0022] As shown in FIGURE 2, the engine 110 generates engine speed and torque outputs  $RPM_{eng}$  and  $TORQUE_{Brake}$  in response to a commanded air/fuel mixture.  $TORQUE_{Brake}$  is commonly referred to as "brake engine torque" and can be derived using estimates of engine indicated torque and engine frictional losses.  $TORQUE_{Brake}$  (also shown as BRAKE\_TQ in FIGURES 2 through 4) can be estimated, for example, using the method described in U.S. Patent No. 5,241,855, entitled "Method and Apparatus for Inferring Engine Torque," which is also owned by the assignee of the present invention and is hereby incorporated by reference in its entirety. The torque converter 212 then converts  $TORQUE_{Brake}$  to converter output torque  $TORQUE_{Turbine}$ , and subject to driveline frictional losses, is transmitted through the transmission 214 to generate a driveshaft torque  $TORQUE_{Driveshaft}$  and driveshaft rotational speed  $RPM_{Driveshaft}$ . SLIP\_RPM in block 212 represents the difference between engine rotational speed and the rotational speed of a torque converter turbine, and GEAR\_RATIO in block 214 the gear ratio of the vehicle transmission. Subject to additional driveline losses,  $TORQUE_{Driveshaft}$  is transmitted through the axle 216 to yield wheel torque  $TORQUE_{Wheel}$  and corresponding wheel rotational speed  $RPM_{Wheel}$ . As such, if the engine indicated torque, brake torque and frictional losses of the engine and driveline are

known, the vehicle speed and torque outputs  $RPM_{Wheel}$  and  $TORQUE_{Wheel}$  at the wheels can be estimated.

[0023] FIGURES 3 and 4 show flow diagrams of preferred methods for operating a variable compression ratio internal combustion engine in accordance with the present invention. The method of FIGURE 3 is applicable to variable compression ratio internal combustion engines operating in discrete compression ratio states, for example the engine described above with reference to FIGURE 1, and the method of FIGURE 4 is applicable to a continuously variable compression ratio internal combustion engine having for example "HI" and "LOW" states representing minimum and maximum limits on a continuous range of compression ratio states. The scope of the present invention however is not intended to be limited to a particular type of engine or compression ratio setting apparatus.

[0024] Referring now to FIGURE 3, a preferred method for operating a discretely variable compression ratio internal combustion engine includes the steps of determining the rotational speed ( $RPM_{eng}$  or engine\_speed) of the engine, step 302, determining the air flow (aircharge) into the engine, step 304, and determining the compression ratio operating state of the engine, step 306. Engine\_speed can be determined using a speed sensor coupled to an engine crankshaft, as shown for example in FIGURE 1, or any other method known in the art. Aircharge is also determined using any known method, including for example using a MAF sensor disposed in the engine intake manifold as shown in FIGURE 1. The compression ratio operating mode can be determined using any known methods, including using a combustion pressure sensor disposed in one or more of the cylinders, or by using a piston position sensor or other sensor coupled to the engine and/or the compression ratio setting apparatus of the engine. The compression ratio operating state can also be derived or inferred using any suitable method, for example as disclosed in U.S. Application Serial No.'s \_\_\_\_\_ (Attorney Docket No. 201-0838) and \_\_\_\_\_ (Attorney Docket No. 201-0839) entitled "Diagnostic Method for Variable Compression Ratio Internal Combustion Engine," which are also owned by the assignee of the present invention and is hereby incorporated by reference in their entirety.

[0025] Next, if the engine is operating in a low compression mode ( $Low\_CR = TRUE$ ), step

308, then a baseline indicated torque value (Base\_ITQ) at MBT spark is selected from Table 1 shown below, step 310:

[0026]

[t1]

Aircharge (lbs/cylinder-filling)	RPM			
	500	1000	2000	6000
0.0025	95	100	105	105
0.0020	75	80	85	86
0.0015	54	60	65	66
0.0010	34	40	45	46
0.0005	17	20	25	26
0.0000	0	0	0	0

[0027] Table 1: Baseline Indicated Torque Values (N-m) for Low Compression Ratio (ITQ\_LO\_CR)

[0028] Table 1 shows predetermined low compression Base\_ITQ (ITQ\_LO\_CR ) values as a function of engine speed (eng\_speed) and air flow (aircharge). Engine\_speed is shown in revolutions per minute (RPM), and aircharge in lbs/cylinder-filling. Aircharge is determined for example as described in U.S. Patent No. 5,241,855 using an MAF sensor output (AM in lbs/minute) divided by the number of cylinder fillings per minute (e.g.,  $RPM * ENG_{CYL}/2$ , wherein ENG\_CYL is the number of available engine cylinders). The ITQ\_LO\_CR values shown above, as well as the predetermined high compression Base\_ITQ values (ITQ\_HI\_CR) shown below in Table 3, can be determined experimentally and depend also on certain operating conditions and parameters of the internal combustion engine, including for example air/fuel ratio (e.g., stoichiometric), percent exhaust gas re-circulation (e.g., 0% EGR), fuel mixture (e.g., 100% gasoline) and the number of firing engine cylinders.

[0029] A baseline engine friction loss value (Base\_FRIC\_TQ) is then determined using Table 2, step 312:

[0030]

[t2]



Aircharge (lbs/cylinder-filling)	RPM			
	500	1000	2000	6000
0.0025	10	12	15	25
0.0020	12	14	17	24
0.0015	14	16	18	23
0.0010	16	18	20	22
0.0005	18	20	21	21
0.0000	20	22	23	20

[0031] Table 2: Baseline Engine Friction Loss Values (N-m) for Low Compression Ratio (FTQ\_LO\_CR)

[0032] Table 2 shows predetermined low compression Base\_FRIC\_TQ values (FTQ\_LO\_CR) also as a function of engine speed and air flow. The FTQ\_LO\_CR values shown above, as well as the predetermined high compression Base\_FRIC\_TQ values (FTQ\_HI\_CR) shown below in Table 4, can be determined experimentally and depend further on certain operating conditions and parameters of the internal combustion engine, including for example engine temperature (e.g., warmed-up engine), whether the engine is "broken-in" (e.g., friction stabilized), whether an air conditioner clutch of the vehicle is disabled, and the base pressure of a power steering system (i.e., hydraulic pressure with steering wheel in "straight ahead" position).

[0033] Referring again to FIGURE 3, step 308, if the engine is operating in a high compression operating state (Low\_CR = FALSE), then Base\_ITQ and Base\_FRIC\_TQ are selected from Tables 3 and 4 respectively:

[0034]

[t3]

Aircharge (lbs/cylinder-filling)	RPM			
	500	1000	2000	6000
0.0025	103	108	113	112
0.0020	82	90	95	96
0.0015	59	66	71	72
0.0010	37	43	48	49
0.0005	19	23	28	29
0.0000	0	0	0	0

[0035] Table 3: Baseline Indicated Torque Values ((N-m) or High Compression Ratio (ITQ\_HI\_CR)

[0036]

[t4]

Aircharge (lbs/cylinder-filling)	RPM			
	500	1000	2000	6000
0.0025	12	14	17	27
0.0020	14	16	19	25
0.0015	16	18	20	25
0.0010	18	20	22	24
0.0005	20	22	23	23
0.0000	22	24	25	22

[0037] Table 4: Baseline Engine Friction Loss Values (N-m) for High Compression Ratio (FTQ\_HI\_CR)

[0038] The Base\_ITQ and Base\_FRIC\_TQ values determined in accordance with steps 310 and 312 (or 314 and 316) can then be modified, adjusted or otherwise changed to take into account certain operating conditions and parameters of the internal combustion engine, steps 318 and 320. Base\_ITQ can be modified as described for example in U.S. Patent No. 5,241,855 using multipliers representative of one or more operating parameters and conditions of the engine. Similarly, Base\_FRIC\_TQ can be combined with selected miscellaneous friction loss values to compensate for variable frictional losses attributable to certain operating conditions and parameters of the internal combustion engine. The adjusted Base\_ITQ and Base\_FRIC\_TQ values, shown as indicated torque (IND\_TQ) and total engine friction loss (TOTAL\_FRIC\_TQ) in FIGURE 3, are then used to derive a value for brake engine torque (BRAKE\_TQ). In accordance with step 322, TOTAL\_FRIC\_TQ is subtracted from IND\_TQ to derive the BRAKE\_TQ estimate.

[0039] FIGURE 4 shows a preferred method for operating a continuously variable compression ratio internal combustion engine in accordance with the present invention. The method is similar to the method of FIGURE 3, except that Tables 1 through 4 are used at all times regardless of the compression ratio operating state of the engine.

[0040] In accordance with FIGURE 4, step 408, an interpolator value is determined in accordance with Equation (1):

[0041] 
$$\text{Interpolator} = (\text{CR\_ACT} - \text{CR\_MIN}) / (\text{CR\_MAX} - \text{CR\_MIN}) \quad \text{Eq. (1)},$$

[0042] wherein CR\_ACT is the actual compression ratio of the internal combustion engine, CR\_MIN is a minimum compression ratio, and CR\_MAX is a maximum compression ratio of the engine. The interpolator value is then used along with the respective tables in accordance with Equations 2 and 3 to derive the Base\_ITQ and Base\_FRIC\_TQ values for a continuously variable compression ratio internal combustion engine:

[0043] 
$$\text{Base\_ITQ\_TQ} = \text{ITQ\_LO\_CR} + \text{Interpolator} * \text{ITQ\_HI\_CR} \quad \text{Eq. (2)}$$

[0044] and,

[0045] 
$$\text{Base\_FRIC\_TQ} = \text{FTQ\_LO\_CR} + \text{Interpolator} * \text{FTQ\_HI\_CR} \quad \text{Eq. (3)}$$

[0046] Base\_ITQ and Base\_FRIC\_TQ values are then modified and BRAKE\_TQ computed as described above with respect to steps 318, 320 and 322 of FIGURE 3.

[0047] Although the present invention has been described in connection with particular embodiments thereof, it is to be understood that various modifications, alterations and adaptations may be made by those skilled in the art without departing from the spirit and scope of the invention. It is intended that the invention be limited only by the appended claims.